A Statistical Model of Central Valley Chinook Incorporating Uncertainty

Description of
Oncorhynchus Bayesian Analysis
(OBAN) for winter run Chinook

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OBAN Project Objective

To develop a statistical modeling approach to the two Central Valley chinook salmon species-at-risk (winter-run and spring-run) that incorporates mortality in all phases of salmon life history, and includes the effects of uncertainty in assessing population status, guiding future research, and making management decisions.

Substantial resources have been devoted to the management of water, fisheries, and habitat in the San Francisco Bay-Sacramento River Delta (Delta) ecosystem. Research has tended to be focused on the controllable freshwater factors that could affect salmon run variability (resident chinook salmon runs in particular), such as flows and diversions, but there has been less emphasis on other sources of variability such as the ocean. The data collection has tended to occur in disparate geographic regions with few attempts at synthesizing the available information into a coherent framework to account for factors affecting all of the chinook life history stages.

In response to these needs, R2 Resource Consultants, Inc. in collaboration with the University of Washington and NOAA Fisheries developed a proposal to meet the following objectives of the 2004 CALFED Proposal Solicitation Package (PSP): construct a "Life Cycle Model" of several "Key Species", and of necessity it must account for all "Stresses" on those species, including "Environmental Influences" and the "Effects of Diversions". It will provide "Prediction and Strategic Assessments for Water Management and will directly improve effectiveness of Monitoring" by reducing unexplained variability in populations through direct accounting for the effects of "Ocean Conditions and Fisheries on Survival" of a salmonid.

The OBAN modeling framework has several key objectives:

1. Develop a model structure that is capable of accounting for mortality during all phases of the Chinook life history.
2. Estimate model coefficients by fitting predictions of the population dynamics model to observed indices of abundance.
3. Evaluate covariates that may explain dynamic vital rates (e.g., thermal mortality reduces alevin survival rates in spawning reaches).
4. Incorporate uncertainty in the estimation of model coefficients by fitting in a Bayesian framework.

To meet these objectives, we constructed a conceptual model for winter run Chinook to identify life history stages to be modeled, factors that are hypothesized to affect these stages, and management actions that may affect the population dynamics. The winter run model is composed of 9 different life history stages that are affected by a variety of environmental and anthropogenic sources (Figure 1).

Spawning

Winter run Chinook spawn between April and August (Fisher 1994). Three spawning areas were identified for inclusion into the model, namely 1) the region above the Anderson Cottonwood Irrigation District (ACID) diversion dam and below Keswick Dam, 2) the region below ACID and above RBDD and 3) the region below RBDD (Figure 1). Data on the distribution of winter run spawners is available through carcass surveys that have been conducted since 1996 (Snider et al. 1997; Snider et al. 1998; Snider et al. 1999; Snider et al. 2000; Snider et al. 2001; Snider et al. 2002; USFWS 2007). Age and gender of spawning winter run Chinook are provided by carcass surveys for fish that spawn above River Mile 275 (CDFG 2004). In addition, aerial redd surveys have been conducted that provide an assessment of the distribution of redds below RBDD (CDFG 2004). Finally, counts at RBDD have been used to estimate the winter run escapement since 1967; however, since 2001 the annual escapement estimates have been calculated using a Jolly-Seber estimator derived from the carcass count data (CDFG 2004). Despite some changes in the operations of RBDD that affect the precision of the spawner escapement estimates (Botsford and Brittnacher 1998), the RBDD counts provide a continuous time series of winter run estimates. Prior to 1987, all returning spawners passed via a counting ladder at RBDD, but from 1987 onwards the gates of the diversion dam have been opened to enhance upstream survival of winter run Chinook, but also likely improved access to areas above RBDD. The current operation of RBDD makes counts of winter run Chinook after closing the gates on May 15. On average, 15% of the winter run passed RBDD by May 15th, however the specific percentage in a given year was as low as 3% or as high as 48% (Snider et al. 2000).

Several factors may have influenced the distribution and abundances of winter run Chinook in the spawning reaches of the Sacramento River. First, changes in the operations of RBDD prior to 1990, as stated above, may have influenced the passage rates of winter run and thus affected spawning abundance above RBDD. Second, addition of a fish ladder in 2001 improved passage past ACID, and the distribution of winter run Chinook appears to be shifting toward reaches above ACID (CDFG 2004). Third, the proportion of hatchery fish contributing to spawner abundance has varied among years. Recent estimates of the proportion of hatchery fish spawning naturally has ranged from 5.8% in 2003 to 19.5% in 2005 (USFWS 2007).

A management action that is likely to affect winter run Chinook spawners is the carryover storage at Shasta Dam, which can affect the temperature profile of the spawning regions. Although temperature may be more important for the survival of eggs, there may also be an effect on adults spawning after May. Other management actions could include gravel supplementation that alters the substrate in the spawning reaches (e.g., Stillwater Sciences 2007). Finally, additional habitat for winter run Chinook spawning may be available on Battle Creek. The Battle Creek Salmon and Steelhead restoration project would potentially open 42 miles of habitat for steelhead, spring, and winter run Chinook (Ward and Kier 1999).

Eggs and Alevins

Eggs are deposited in the gravel between April and May and emerge between July and October (Fisher 1994). The number of eggs in specific spawning regions can be calculated as a function of length fecundity relationships for winter run Chinook (e.g., relationships described in Williams 2006), the distribution of redds among the spawning regions, and estimates of abundance of the spawning population for a given year.

Factors that were identified as affecting egg survival were the substrate quality and thermal mortality. Egg survival may be affected by substrate composition and quality in the spawning regions. Estimates of the gravel quality below Keswick Dam have provided some indication of the effect of gravel supplementation that has occurred in the spawning regions since 1978 (Stillwater Sciences 2007). In addition, egg survival in the three spawning regions may be affected by the thermal conditions during incubation. Determining the thermally induced mortality rate requires developing relationships between temperature conditions in the spawning regions and egg survival. There are at least two sources of information for providing initial estimates of the relationship between thermal conditions and egg mortality. First, the thermal mortality rates of winter run Chinook eggs was studied by USFWS (1999), in which eggs were incubated at different temperatures with subsequent observations of mortality rate. Second, the thermal mortality for years between 1989 and 1996 were calculated by NMFS 1997).

Management actions that are likely to affect the egg stage are similar to those described for spawning, namely gravel supplementation and temperature management. Because the temperature profile of water leaving Keswick dam can be managed with hypolimnetic releases from Keswick via the temperature control device the temperature in the spawning regions can therefore be modified independently of flow.

Rearing above RBDD

Fry emerge from the gravel between July and October (Fisher 1994). For the purposes of the model, fry from each of the spawning regions combine to form a unified population of rearing winter run Chinook above RBDD. Winter run Chinook migrate past RBDD between August and October as fry (Poytress 2007).

Estimates of the number of winter run fry that pass RBDD are calculated from samples of winter run juveniles in screw traps (e.g., Poytress 2007). The juvenile estimates provide an index of the amount of winter run juvenile production that occurred in the spawning reaches. Moreover, for the purposes of the model, the data provide a source of evaluating factors that affect the survival rate between spawning and RBDD versus factors that affect winter run from RBDD to spawning. For this reason, the two data sources (adult escapement and juvenile estimates at RBDD) were used previously by Newman and Lindley (2006) for the construction of a population dynamics model for winter run Chinook.

Factors that may affect juvenile rearing above RBDD include Sacramento River flow and diversions that are used to support rice farming in the Upper Sacramento River.

RBDD to Chipps Island (Lower Sacramento and Delta)

Winter run migrate through the lower Sacramento River and Delta from October through May. Generalized estimates of timing based on genetic identification of winter run indicated that winter run Chinook are at Knights Landing during December, Lower Sacramento River between December and March, and in the Central Delta from March through May (approximations from data presented in Hedgecock 2002 as cited in Williams 2006).

Several sources of information could potentially be used to determine the timing and relative abundance of winter run Chinook in the lower Sacramento and Delta, if individuals could be more accurately identified to run type. For example, salvage data may provide sources of information regarding the timing of Chinook into the Delta. The year type (i.e., wet versus dry) and the amount of export pumping appears to affect the number of Chinook entrained at the pumps, however (Williams 2006). In addition, trawl data from Chipps Island could provide information on the run timing, and relative abundances of winter run Chinook. The trawls at Chipps Island are a particularly interesting source of data because the locations of the trawls are at the terminus of the Delta. Thus, accurate indices of abundance for winter run Chinook would be helpful in determining how the production of fry in the spawning regions fared through the lower Sacramento River and Delta.

Unfortunately, at this point in time the method for discerning runs (namely length at date criteria) may create biases in the data (Williams 2006). The biases appear to overestimate the number of winter run, because other runs also have similar lengths at a particular date (Hedgecock 2002 as cited in Williams 2006). Thus, indices of winter run abundance from Chipps Island trawls may over estimate the size of the outmigrating population, whereas estimates of mortality at the CVP and SWP facilities from salvage data might overestimate mortality. The level of overestimation appears to vary among years and may range from 16% to 95%, however (Williams 2006). Genetic analyses from salvage data and Chipps Island trawls are attempting to determine the proportion of winter run Chinook in specific length at date categories and whether the run identification can be improved.

Several factors were identified in the technical meeting that may influence survival in the juvenile stage between RBDD and Chipps Island:

- Delta Cross Channel gate position
- Entrainment Risk (e.g., Kimmerer and Nobriga 2008)
- Rearing in Yolo and Sutter Bypass
- Adult striped bass indices of abundance

The geographical area is similar to the region used in Newman and Rice (2002) and Newman (2003). Although the coefficients estimated in those analyses are not directly applicable to winter run (for example, the temperatures experienced by winter run Chinook are below that experienced by fall run), evaluation of a similar geographical region provides an opportunity to compare estimates. Additional covariates used in the Newman (2003) analysis that could be included as factors are Sacramento River flow, export volumes, salinity, turbidity, and tidal influence.

Chipps Island to Golden Gate (Bays)

The duration of use of the bays downstream of Chipps Island (Suisun Bay, San Pablo Bay) and the Central Bay by winter run Chinook is largely unknown. Recent studies by MacFarlane and Norton (2002) on fall run Chinook suggest that there may not be much growth during this phase of the migration, and that juveniles may transition relatively quickly to the Gulf of the Farallones; on average juvenile salmon in the study took approximately 40 days to complete the 68 km trip from Chipps Island to Golden Gate. After reaching the Gulf of Farallones, the growth rates of sampled Chinook increased, and the stomach contents of the sampled juveniles in the Farallones was composed of fish larvae, decapod larvae and megalopae, and euphausiids.

How to apply these inferences, which targeted fall run in a single year, is difficult. There is some evidence that larger Chinook may pass through the estuary quicker than smaller Chinook (Bottom et al. 2005). Winter run Chinook are typically larger than fall run Chinook after rearing for several months in the lower Sacramento and Delta, thus their use of the Bay may be somewhat abbreviated relative to fall and spring run Chinook.

One factor that may affect survival rates of winter run Chinook is predation by adult striped bass both in the Delta and in the bays leading to the Golden Gate Bridge.

Golden Gate through the Farallones (Nearshore Ocean Stage)

The timing of winter run entry into the ocean is assumed to be the late spring and early summer in advance of fall and spring run Chinook. Given the patterns in estuary versus nearshore use described by MacFarlane and Norton (2002), much of the development after Chipps Island may occur in the nearshore.

Factors affecting the nearshore ocean stage include the amount of food available for consumption during this stage. Evidence from fall run Chinook studies (e.g., MacFarlane et al. 2005) suggested that growth rates during the early ocean phase between 1997 and 1999 were on the order of 0.5 to 0.8 mm d^{-1}, whereas the estimated growth rate for 1997 in the bays was approximately 0.18 mm d^{-1} (McFarland and Norton 2002). In addition, condition factor of juvenile Chinook in the nearshore increased from approximately 1.03 at entry to the ocean to 1.42 and 1.32 in 1998 (an el Niño year) and 1999 (a la Niña year), respectively (MacFarlane et al. 2005). These results support the importance of the nearshore environment for growth of juvenile Chinook.

Several factors may influence the nearshore stage related to the timing and level of productivity of the nearshore environment during the late spring and early summer. Indices of ocean condition, such as the spring sea surface temperature (SST) and Pacific Decadal Oscillation (PDO) index may provide indications of ocean condition. In addition, upwelling indices and the seasonal timing of upwelling may be useful for determining the productivity at the time of ocean entry (e.g., Wells et al. 2007). Direct measurements of zooplankton such as krill indices of abundance may provide information on prey availability. In addition, indirect measures of productivity, such as nesting success of Cassin's Auklet, may provide information on nearshore productivity over longer time periods.

Because there are no surveys that target winter run Chinook in this stage, the influence of the nearshore stage will be evaluated by fitting to residuals of models fitted to RBDD juvenile indices of abundance (e.g., JPI) and adult escapement estimates.

Ocean Stages

The distribution of winter run Chinook sub adults in the ocean tends to occur from San Francisco to Monterrey based on CWT data from 1998 to 2002 of hatchery reared winter run reared at Livingstone Stone National Fish Hatchery (Williams 2006, and data from the Regional Mark Information System).

Fishing and natural mortality are likely the two main factors that will influence the population dynamics of winter run Chinook in the ocean. Natural mortality is assumed to be higher for salmon in their first year of ocean residency, thus model estimates of natural mortality would be expected to be higher for winter run Chinook in their first year of ocean residency versus second or third years. Fishing effort may be an important determinant of fishing mortality and efforts to recreate the fishing effort on winter run may provide an important covariate for explaining changes in the ocean stage abundances. Estimates of the ocean harvest rate have been completed previously (e.g., Cramer et al. 2004, Wim Kimmerer, SFSU personal communication 2005). The approach was similar in both cases, and estimates of harvest rates during periods when winter run were implanted with CWTs (1969 – 1971 and 1995 - present) were compared to the overall index of harvest rates on Central Valley Chinook Harvest Index. The relationship developed over those periods was used to interpolate during periods when a winter run specific estimate of ocean harvest rate was not available. Fish that return to freshwater may be harvested in a sport fishery and estimates of in river fishing mortality can be derived in similar fashion to the ocean fishery (e.g., Cramer 2004; Grover et al. 2004).

Winter run Chinook are too small to be exposed to the fishery in their first summer in the ocean; however, by the second summer in the ocean they are within the size limitations for the ocean fishery and have been captured historically. Fishery regulations have been altered to minimize the amount of winter run harvest mortality; therefore, less information has been collected on winter run in the ocean fishery as time has elapsed.

Most winter run return from the ocean to freshwater after their second summer in the ocean (age 3 fish), entering San Francisco Bay beginning in November. A small proportion of a winter run Chinook cohort remains in the ocean for a third summer, are potentially exposed to harvest, and return as age 4 fish. Estimates of the age composition are provided by reconstructing the cohort through evaluation of CWT data from spawner surveys, fishery returns, and hatchery returns (Grover et al. 2004).

OBAN Implementation

The winter run Chinook OBAN model has been developed from the conceptual life-cycle model of winter run and coded into Windows based software with graphic output capability. The estimation of model coefficients was coded into AD Model Builder, which is an estimation algorithm designed specifically for non-linear models (Fournier 2001). The software finds a statistical "best fit" to empirical trends by matching model predictions to empirically observed juvenile and adult abundances. The model is capable of fitting any number of abundance data sources and estimating any number of coefficient values to find the best statistical prediction.

The model has the flexibility to mimic distinct spawning populations that merge into a common freshwater population that subsequently migrates to the ocean. Once in the ocean, the population either returns to spawn in one, two or three years. The model predicts the abundance of juveniles at 6 stages of fresh water life history and 3 stages of ocean life history. The first two stages of fresh water dynamics (spawning and alevin) occur as three distinct populations (above Red Bluff diversion dam (RBDD), Acid to RBDD and below RBDD). At the end of the second stage, the populations merge into a single population below RBDD and migrate to the ocean as a unit through the fry, delta, bay and gulf stages. Prior to merging, each population is subject to demographic rates and environmental conditions which can be assumed to be distinct or common to all populations. After merging, all demographic rates and environmental conditions are common in each stage but distinct among stages. The model is being fit to spawning estimates from 1967 to 2005 and juvenile production indices at Red Bluff Diversion Dam from 1995 to 2006.

The transition between life history stages occurs with a Beverton-Holt recruitment function:

$$N_{i,j+1} = N_{i,j} \times \frac{p_{i,j}}{1 + \frac{p_{i,j} N_{i,j}}{K_{i,j}}}$$

where $N_{i,j}$ is the abundance at stage *j* for stock *i*, $p_{i,j}$ is the productivity in the absence of density dependence for spawning stock *i* at stage *j*, $K_{i,j}$ is the capacity at stock *i* at stage *j*. The two parameters of the Beverton-Holt transition equation are $p_{i,j}$ and $K_{i,j}$, and they can be user defined constants, estimated parameters fixed across all years, or dynamic, i.e., $p_{i,j,t}$ and $K_{i,j,t}$ can be modeled as changing in each year *t*. Note that density dependence can be effectively removed from the formulation by setting $K_{i,j}$ to a very large value.

In the case of dynamic productivity ($p_{i,j,t}$) and capacity ($K_{i,j,t}$), parameter values, the values of the productivities and capacities in a given year are modeled from a set of time-varying covariates. By using this formulation, we can evaluate the influence of anthropogenic and environmental factors on specific life history stages. Each productivity parameter can be influenced by up to five independent covariates acting simultaneously on the life history stage to drive demographic rates. The $X_{j,t}$ are environmental variables that represent water conditions such as temperature or flow, biotic factors such as predator abundance, food abundance, or anthropogenic factors such as water export levels or harvest rates.

The dynamic productivities used a logit () transformation, which caused the productivities to remain between 0 and 1. This interval is the sample space for the survival for all stages from alevin to spawner.

$$\mathrm{logit}(p_{i,j,t}) = \beta_{0,i,j} + \beta_{1,i,j} X_{1,i,t} + \beta_{2,i,j} X_{2,i,t} + \ldots + \beta_{5,i,j} X_{5,i,t}$$

$$p_{i,j,t} = \frac{\exp(\beta_{0,i,j} + \beta_{1,i,j} X_{1,i,t} + \beta_{2,i,j} X_{2,i,t} + \ldots + \beta_{5,i,j} X_{5,i,t})}{1 + \exp(\beta_{0,i,j} + \beta_{1,i,j} X_{1,i,t} + \beta_{2,i,j} X_{2,i,t} + \ldots + \beta_{5,i,j} X_{5,i,t})}$$

The dynamic capacities used a log() transformation, which caused the capacities to remain between 0 and infinity. This interval is the sample space for the abundance for all stages from alevin to spawner.

$$\ln(K_{i,j,t}) = \beta_{0,i,j} + \beta_{1,i,j} X_{1,i,t} + \beta_{2,i,j} X_{2,i,t} + \ldots + \beta_{5,i,j} X_{5,i,t}$$

The estimation of $p_{i,j,t}$ and $K_{i,j,t}$ involves estimating the β parameters. If no environmental effect is being estimated, only β_0 is estimated and the remaining β's are set to zero. If $p_{i,j}$ and $K_{i,j}$ are not estimated, but rather set as constants, then β_0 is selected such that p or K equates to the desired rate, i.e., $\beta_0 = \ln(p / (1-p))$ or $\beta_0 = \ln(K)$.

The model has the ability to estimate as few or as many of the parameters as desired. We used Akaike's Information Criterion for small sample sizes (AIC_C, Burnham and Anderson 2002) to evaluate the utility of adding additional parameters. Estimating a fixed rate involves one additional parameter (β_0) and estimating relationships to a covariate involves adding a β parameter for each additional covariate.

The process has been implemented with a Graphic User Interface (GUI) that provides ease of access to model customization. The model dashboard provides a method to define a specific model by indicating whether the capacity or productivity in a particular stage will be estimated as a fixed rate or as a function of covariates. The predicted population dynamics are displayed on the main GUI form after fitting the specified model form (Figure 2). Furthermore, the GUI also allows the user to manipulate which parameters are being estimated and to associate the covariates with the proper β parameter. A windows form is used to toggle estimation and file locations as well as to view the values of β's as they are estimated (Figure 3).

The winter run OBAN model has been constructed such that users can evaluate hypotheses about factors affecting the winter run population dynamics. In its present state, the model can estimate the influence of 5 environmental covariates for each spawning reach and stage. Currently, there are several covariate files that have been constructed to explain the winter run population dynamics based on the winter run conceptual model: potential for thermal mortality during the summer (NMFS 1997), minimum flow past RBDD between August and December in the brood year, exports between January and March of the brood year, the number of days that the Yolo bypass had flows greater than 2000 cfs (the capacity of the toe drain), an estimate of striped bass adult abundance from catch per fishing vessel records, the Pacific Decadal Oscillation (PDO) index, and the Central Valley Harvest Index in the returning year. All of these covariates have been standardized to have a mean of zero and a standard deviation of one.

The model can also be used to evaluate covariates to test new hypotheses. Provided the user can construct a time series of the covariate of interest from 1967 to 2004 and standardize it, the user can incorporate the new covariate as a predictor of either productivity or capacity (e.g., Figure 3) and run the model and evaluate the improvement in fit due to adding the covariate (e.g., Figure 2).

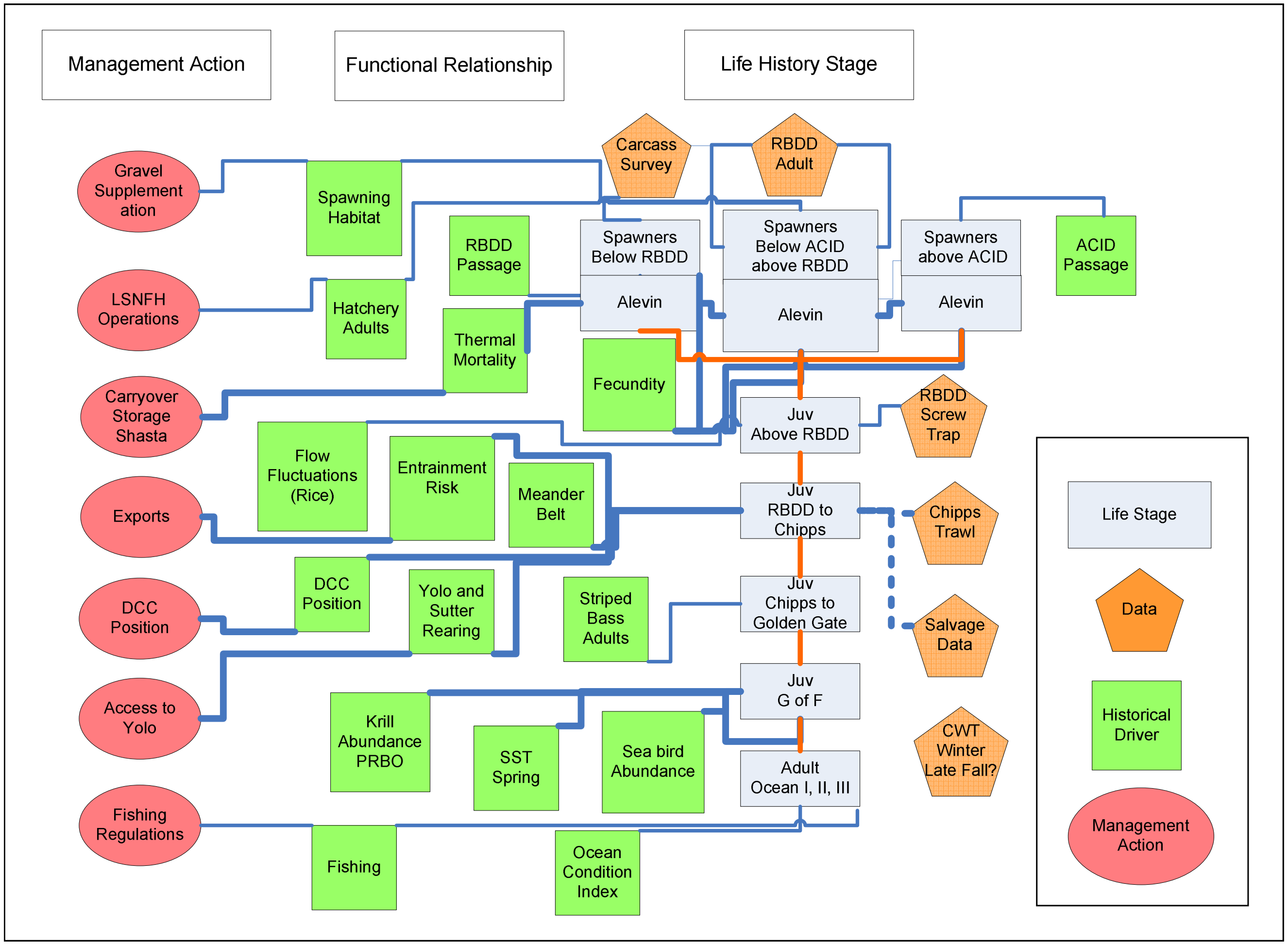


Figure 1. Winter run Chinook conceptual model indicating spatio-temporal partitioning of life history stages, data for specific life history stages, possible environmental and anthropogenic drivers of historical trends in abundance, and potential management actions that would affect recovery. Orange lines indicate transition of individuals through the stages, whereas blue lines indicate factors affecting abundance. The weight of lines are altered for alternating stages to improve visualization of the linkages from data, drivers, and actions to life history stages.

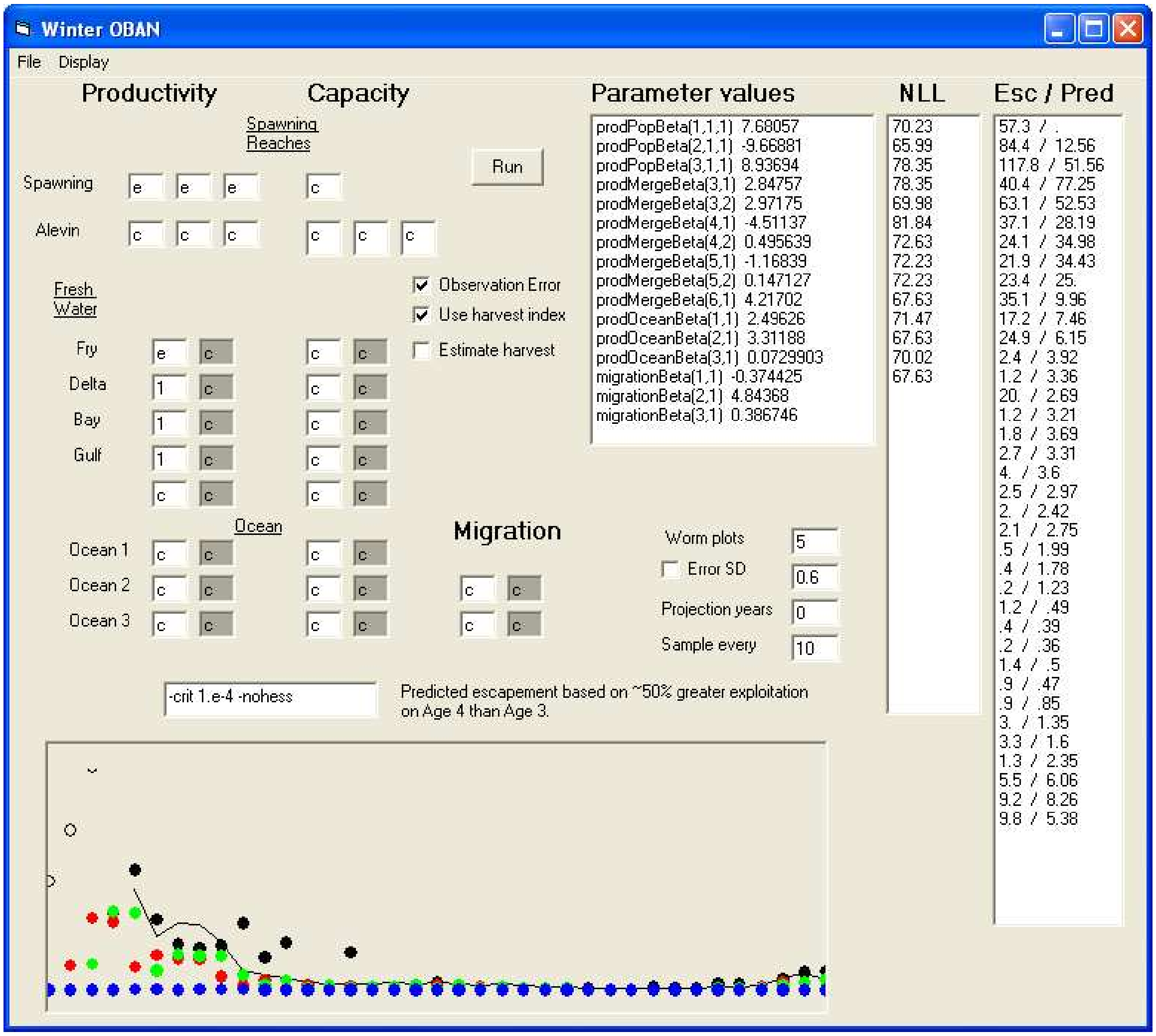
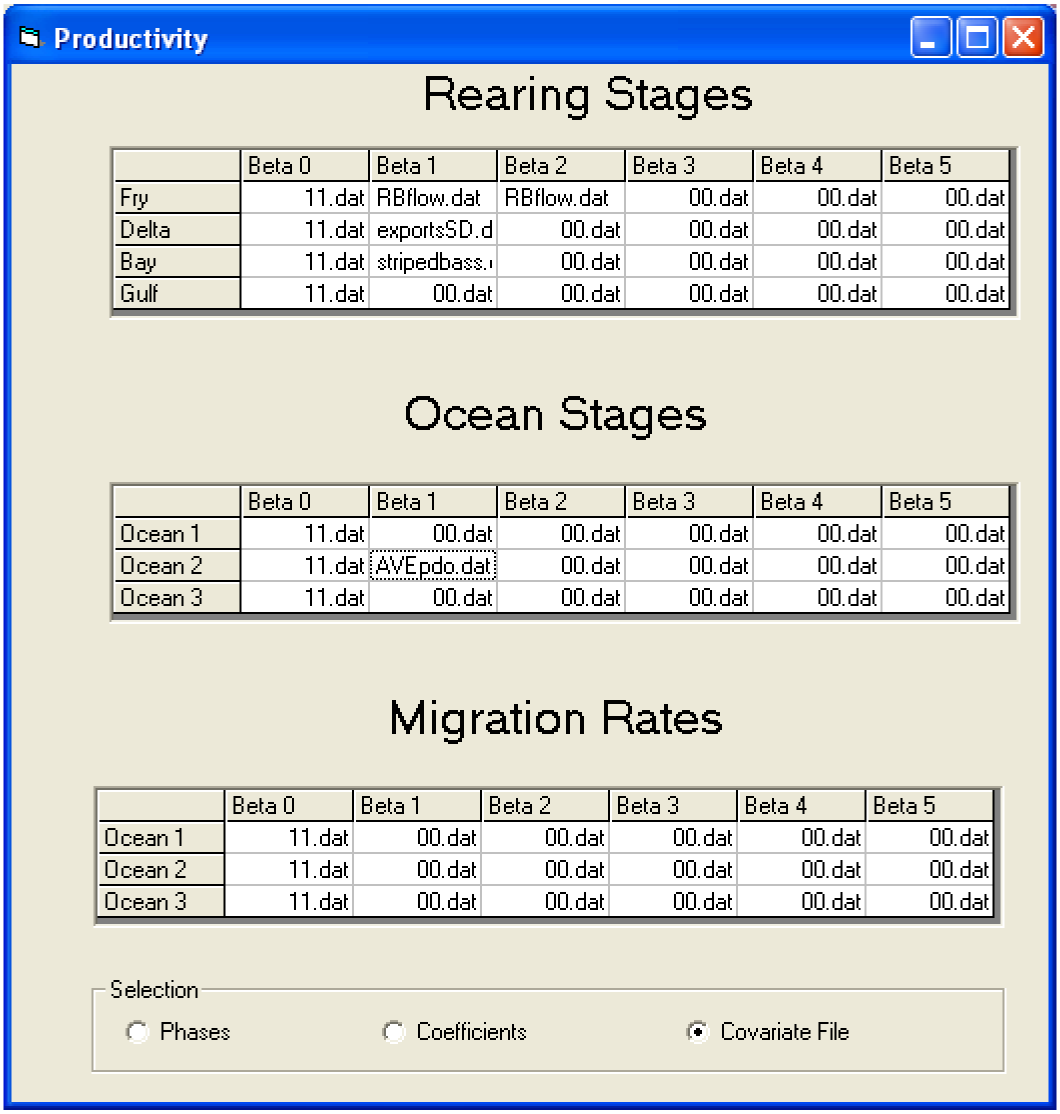


Figure 2. Graphical User Interface (GUI) of winter OBAN model. The GUI provides the ability to change the model structure by identifying whether the coefficients of specific life history stages will be constant ("c"), estimated ("e"), or a function of covariates ("1", .."5"). The GUI also provides a plot of the model fit to the adult escapement data (model predictions [lines], escapement data [black points], assumed age structure [colored points]), estimates of the coefficient values, and the negative log likelihood (NLL) between model predictions and observed escapement.



	Beta 0	Beta 1	Beta 2	Beta 3	Beta 4	Beta 5
Fry	11.dat	RBflow.dat	RBflow.dat	00.dat	00.dat	00.dat
Delta	11.dat	exportsSD.d	00.dat	00.dat	00.dat	00.dat
Bay	11.dat	stripedbass.	00.dat	00.dat	00.dat	00.dat
Gulf	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat

	Beta 0	Beta 1	Beta 2	Beta 3	Beta 4	Beta 5
Ocean 1	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat
Ocean 2	11.dat	AVEpdo.dat	00.dat	00.dat	00.dat	00.dat
Ocean 3	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat

	Beta 0	Beta 1	Beta 2	Beta 3	Beta 4	Beta 5
Ocean 1	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat
Ocean 2	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat
Ocean 3	11.dat	00.dat	00.dat	00.dat	00.dat	00.dat

Figure 3. Graphical User Interface (GUI) of winter OBAN showing the interface that allows the user to set the model structure by changing whether coefficients are estimated (Phases), allows the user to define the covariate file (Covariate File), and allows the user to view the coefficient estimates (Coefficients).

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